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Sahlin, Eva A. U.; Glasser, Neil F.; Jansson, Krister N.; Hambrey, Michael J.

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Eva A.U. Sahlin, Neil F. Glasser, Krister N. Jansson,
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Connectivity analyses of valley patterns indicate preservation of a preglacial fluvial valley system in the Dyfi basin, Wales

Eva A.U. Sahlin, Neil F. Glasser, Krister N. Jansson, Michael J. Hambrey.

Abstract

Coastal valleys in the west part of Mid-Wales, such as the Mawddach, Dysynni, Tal-y-llyn and Dyfi, acted as corridors for ice which drained the Welsh Ice Cap during the Devensian. Analyses of detailed digital elevation models, and interpretation of satellite images and aerial photographs, show the existence of large variations in the amount of glacial modification between these valleys. Although all the valleys are glacially over-deepened along late Caledonian fault lines, only the Dyfi basin exhibits a dendritic pattern, with V-shaped cross-profiles and valley spurs typical of valleys formed by fluvial processes. Connectivity analysis of the Dyfi basin shows that it exhibits an almost completely dendritic pattern with connectivity α and β values of 0.74 and 1.01, respectively, with little glacial modification of the preglacial fluvial valley pattern in the form of glacial valley breaching. Several examples of glacial meltwater incision into a well-developed pre-existing river valley system, causing river capture across watersheds, have been identified in the Dyfi basin. The degree of preservation of the preglacial fluvial valley system within the Dyfi basin indicates limited modification by glacial processes, despite the area being subjected to glacier activity during the Late Devensian at least. It is possible that major parts of the basin were covered by cold-based or slow-moving ice, close to, or under, a migrating ice-divide, with the major ice drainage occurring along the weaker zone of the Pennal Fault along which the Dyfi valley is located, causing minor adjustments to the surrounding interfluves and uplands. It is proposed here that the general river valley morphology of the Dyfi basin is of a pre-Late Devensian age.

1. Introduction

1.1. Rationale

Previous glacial reconstructions of Wales have described the Mawddach, Dysynni, Tal-y-llyn and Dyfi valleys in western Mid-Wales as major drainage conduits for the Welsh Ice Cap (e.g. Smith and George, 1961; Foster, 1968; Garrard and Dobson, 1974; Cave and Hains, 1986; Pratt et al., 1995; Hubbard et al., 2009). However, there are notable differences in the extent of glacial modification between these westwards-draining valleys. Most notable is the difference between the Tal-y-llyn valley, probably the best developed glacial trough in Mid-Wales (Watson, 1962; Campbell and Bowen, 1989), and the adjacent Dyfi basin which exhibits a well-developed dendritic drainage pattern (Fig. 1), where several valleys display V-shaped cross profiles and valley spurs typical of valleys formed by fluvial processes (Sahlin, 2008).

Against this background, the aims of this paper are: (1) to use the landform record to provide insight into glacial landscape modification in the Afon Dyfi Basin, Mid-Wales, and (2) to consider the implications for palaeoglaciological reconstructions of the Welsh Ice Cap.

1.2. Landscape modification by ice sheets

It is now known that the pattern of erosion and deposition and thus the distribution of landforms and sediments within an ice sheet are related to the basal thermal regime (e.g. Sugden, 1974, 1977; Benn and Evans, 1998; Glasser and Bennett, 2004; Kleman and Glasser, 2007). Warm-based ice sliding over its bed, or moving over a deformable bed, has a greater potential for flow and therefore a greater potential for erosion (e.g. Sugden and Watts, 1977; Hallet, 1979; Alley et al., 1997), compared with cold-based ice frozen to its bed (Echelmeyer and Zhongxiang, 1987) (Fig. 2). Understanding spatial variations in ice sheet basal thermal regime is therefore critical for reconstructing palaeoglaciology (e.g. Kleman, 1994; Kleman and Borgström, 1996; Kleman et al., 1997; Clark, 1999; Kleman and Hättestrand, 1999).

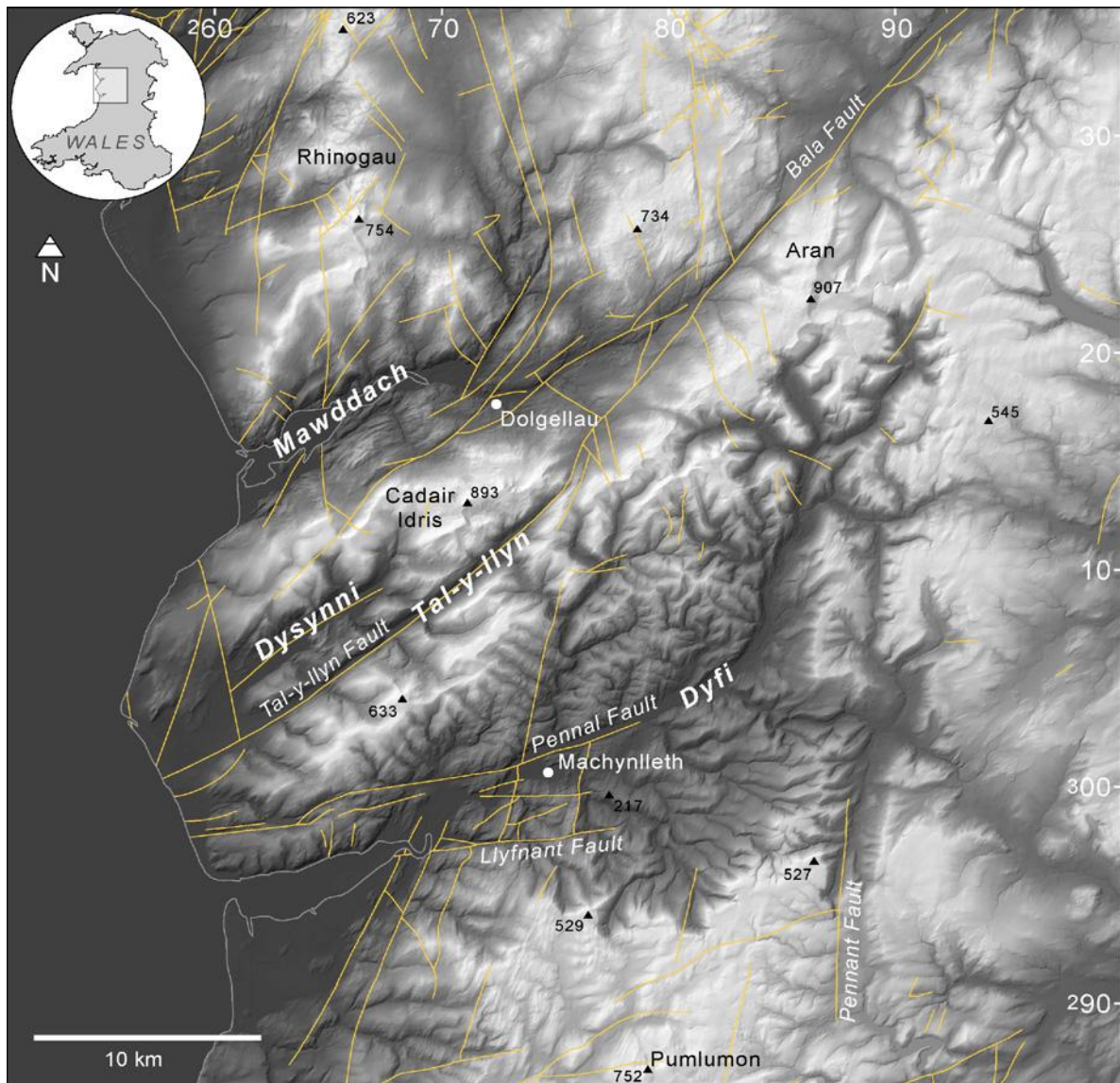


Fig. 1. Relief-shaded digital elevation model (DEM) of drainage pattern and major faults (marked with thin white lines) in northwest Mid-Wales. (Geological fault data for the interior of the Dyfi basin is exempt from the figure as the map sheets 150 and 164 remain (as of September 2009) unpublished by the British Geological Survey.)

Glacial landscapes consist of different landform systems of disparate ages, where pre-Quaternary landforms and sediments (e.g. Battiau-Queney, 1981, 1984; Lidmar-Bergström, 1995, 1997; Kleman and Stroeven, 1997; Rowberry et al., 2007), as well as landforms and sediments from Quaternary glacials and interglacials, have been preserved (e.g. Sugden and Watts, 1977; Lagerbäck, 1988a,b; Lagerbäck and Robertson, 1988; Kleman and Borgström, 1990; Dyke et al., 1992; Dyke, 1993; Kleman, 1994; Rea et al., 1996; Clark, 1993; Hättestrand and Stroven, 2002; Clark and Stokes, 2003). These landscapes, with remnants of landforms and sediments pre-dating the last deglaciation, are often referred to as palimpsest (Kleman, 1992). They are mainly found in areas where the ice sheet was cold-based, such as in relation to thin and slow-moving ice, or close to former ice-divide positions (Boulton and Clark, 1990a,b; Clark, 1993; Jansson and Glasser, 2005). Cold-based core areas are suggested to have been a normal feature of Pleistocene mid-latitude ice sheets (e.g. Huybrechts and

T'siobbel, 1995). As cold-based conditions normally preclude basal sliding and the formation of new glacial landforms, the absence of glacial landform evidence constitutes a major obstacle in tracing these types of glacier thermal conditions. However, cold-based conditions may still leave traces in the form of glaciofluvial landforms, such as lateral and proglacial meltwater channels, during deglaciation (e.g. Sugden and John, 1976; Rohde, 1988; Kleman et al., 1992; Dyke, 1993; Kleman and Borgström, 1996; Hättestrand, 1998; Jansson, 2002).

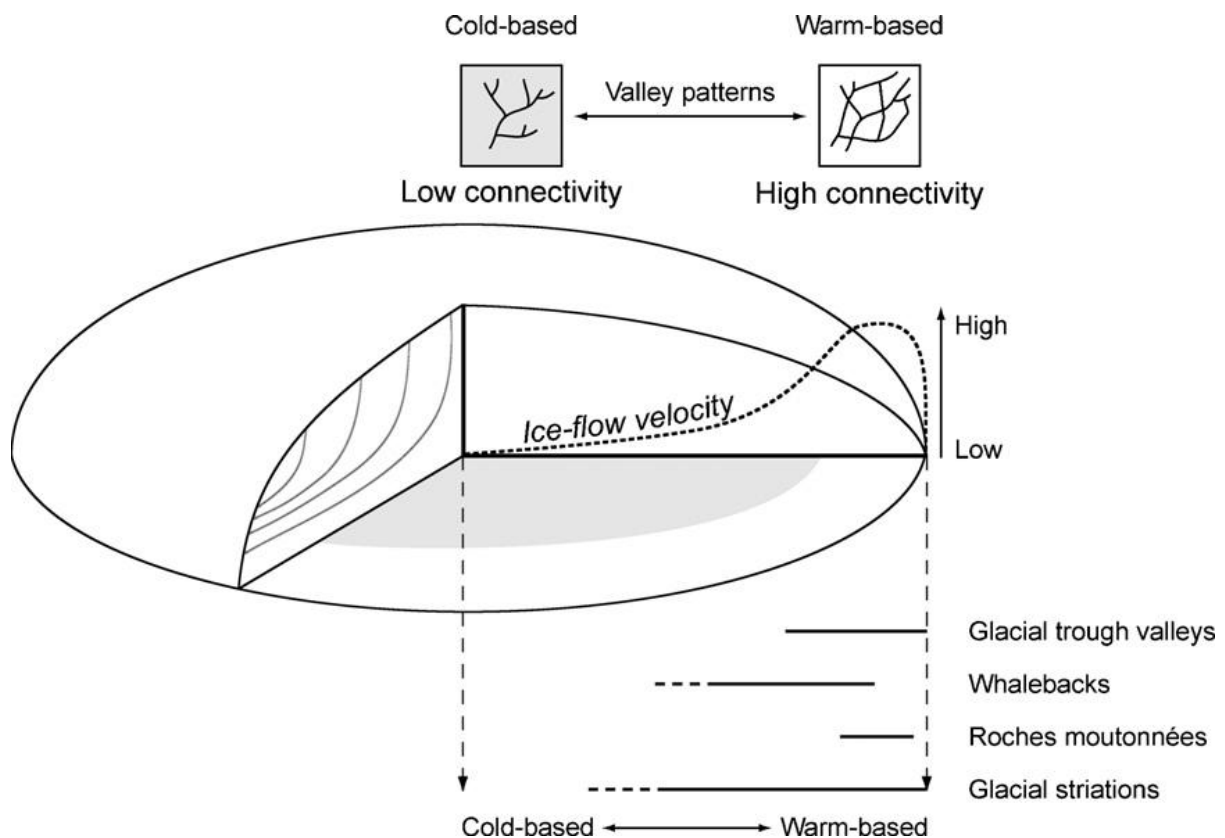


Fig. 2. Schematic cross-section through an ice sheet, showing the relationship between ice-flow velocity, glacial erosion and valley pattern connectivity (after Bennett and Glasser, 1996).

1.3. Modification of valley patterns by glacial erosion

One of the most fundamental and distinctive ways in which warm-based ice sheets modify topography is by altering the valley pattern (Haynes, 1977). A fluvial landscape is generally characterised by a dendritic drainage pattern (e.g. Haynes, 1977; Riedel et al., 2007), with irregular branching of tributaries, V-shaped cross-profiles, smooth concave long profiles, no glacial over-deepening or valley steps, and the occurrence of stream piracy and wind gaps. Where these occur in a formerly glaciated area they are commonly assumed to represent the preglacial landscape (Haynes, 1977), given that ice sheets commonly modify the landscape by watershed breaching, which results in a high interconnectivity between the valleys (Fig. 2). Other landscape characteristics of glacial modification include long

interconnected valleys, barbed tributaries, underfit streams, and low-elevation mid-valley divides (Riedel et al., 2007). A high level of interconnectivity is commonly associated with an increased amount of glacial erosional landforms. Mountain glaciation tends not to alter the preglacial dendritic pattern significantly, whereas the drainage will become increasingly modified by multiple watershed breaching during, or under, the transition to, or from, full scale glaciation (Haynes, 1977). Low levels of interconnectivity may not only be due to modest glacial modification, but also to strong radial glaciation which prevents through-flow from externally derived ice. It is therefore important to consider the distribution of areas of local glaciation (Haynes, 1977). Valley widening can also be caused by paraglacial rock-slope failure (Jarman, 2002, 2006, 2009), especially around watersheds which are undergoing breaching by transfluent ice. The rock-slope failure deposits in their turn may cause watershed breaching, both by ice-drainage deflection, as well as river relocation, leading to the lowering of cols (Korup et al., 2006).

The amount of glacial erosion a landscape exhibits is important for a number of reasons. First, it can provide information on long-term landscape and landform evolution (Lidmar-Bergström, 1995, 1997; Kirkbride and Matthews, 1997). Second, landscapes preserved under cold-based glacial conditions provide a window on the past, and a reference from which to view surrounding areas affected by wet-based and eroding ice (Kleman, 1994). Third, the spatial variation of glacial erosion intensity can be used to infer variations in ice-sheet properties and processes (e.g. Sugden, 1977; Kleman and Borgström, 1994); and therefore provides important information for testing models of ice-sheet dynamics (e.g. Glasser, 1995; Bradwell et al., 2008; Kaplan et al., 2009; Hubbard et al., 2009).

2. Palaeoglaciological and physical setting

2.1. The last British–Irish Ice Sheet

Reconstructions of the Late Devensian British–Irish Ice Sheet (BIIS) traditionally describe the ice mass as a configuration of several independent ice domes, where the offshore reach of the BIIS was limited (e.g. Bowen et al., 1986, 2002). New geochronological data have shown that the BIIS was a long-lived feature that probably existed for much of Devensian (Weichselian) time as a mobile and sensitive ice sheet, with large fluctuations in its marginal positions and centres of mass, in which the Last Glacial Maxima (LGM) was but one important event at about 22 ka (Clark and Meehan, 2001; Bowen et al., 2002; Evans et al., 2009; Hubbard et al., 2009). Recent offshore bathymetry, borehole and seismostratigraphic data, cosmogenic radionuclide dating, and subsequent glacial numerical models proposed for the dimensions of the BIIS at the LGM, indicate an ice sheet much more extensive than previously believed (Sejrup et al., 2005; Ó Cofaigh and Evans, 2007; Bradwell et al., 2008; Hubbard et al., 2009; Ballantyne, 2009), for example the Irish Sea Glacier is believed to have reached the Isles of Scilly (Scourse and Furze, 2001; Hiemstra et al., 2006; Scourse et

al.,2009), rather than terminating in the southern Irish Sea (Bowen et al., 1986) (Fig. 3). The new understanding of the ice-sheet extent implies much thicker ice for various upland source areas (Ballantyne, 2009; Ballantyne et al., this issue), than is depicted in most models for the last BLS (e.g. Lambeck, 1993, 1996).

2.2. The Welsh Ice Cap

Wales was repeatedly covered by a terrestrially based Welsh Ice Cap (e.g. McCarroll and Ballantyne, 2000; Jansson and Glasser, 2005, 2008), in addition to the Irish Sea Glacier that encroached on the coast (e.g. Bowen, 1973, 1977; Thomas, 1985, 2005; Eyles and McCabe, 1989; Glasser et al., 2001; Hambrey et al., 2001; Patton and Hambrey, this issue). The Welsh Ice Cap was semi-independent of the BLS and had several dispersion centres in the upland areas of North and Mid-Wales (e.g. McCarroll and Ballantyne, 2000). The nature of the interactions between the Welsh Ice Cap and the Irish Sea Glacier are still not fully known (Lewis and Richards, 2005; Jansson and Glasser, 2005), and the vertical extent of the Welsh Ice Cap continues to be debated (cf. Shakesby et al., 2007; Jansson and Glasser, 2008; Shakesby and Matthews, 2009).

Glacial reconstructions by Jansson and Glasser (2005) describe the initiation of the Welsh Ice Cap as characterised by ice flowing out from an ice-dispersal centre situated over the higher terrain in north-central Wales, with an ice-divide aligned roughly in a north–south orientation corresponding to the present watershed. The Welsh Ice Cap was probably thickest to the north of Cadair Idris, between the Rhinog Mountains and Arenig Fawr (Foster, 1968, 1970; Campbell and Bowen, 1989; Hughes, 2002a). The high elevation interiors of the ice cap may have been covered by cold-based ice, with ice thick enough to cover the mountain summits (Jansson and Glasser, 2005). Alternatively, the ice was relatively thin, and the higher summits, such as Cadair Idris and Aran Fawddwy, projected above the ice cap as nunataks (McCarroll and Ballantyne, 2000; Ballantyne, 2001).

From the interior of the Welsh Ice Cap, the ice in Mid-Wales was funnelled and discharged westward through the major valleys (Foster, 1968; Addison, 1990; Pratt et al., 1995; Etienne et al., 2005; Jansson and Glasser, 2005), exploiting and over-deepening preexisting valleys developed along lines of structural weaknesses (cf. Cave and Hains, 1989; British Geological Survey, 1995; Pratt et al., 1995). The outlet glaciers from the Welsh Ice Cap ice then coalesced and merged with the Irish Sea Glacier (e.g. Pratt et al., 1995; Hambrey et al., 2001), or became blocked by the more powerful Irish Sea Glacier (Garrard and Dobson, 1974). At the time of the LGM, large parts of interior Wales are believed to have been covered by a cold-based ice dome (Jansson and Glasser, 2005). Following the disappearance of ice in the southern Irish Sea and before the final deglaciation of northeast Wales, the dynamics of the Welsh Ice Cap went through an abrupt change when

topographically controlled ice streams began to drain the ice cap in northern and eastern Wales.

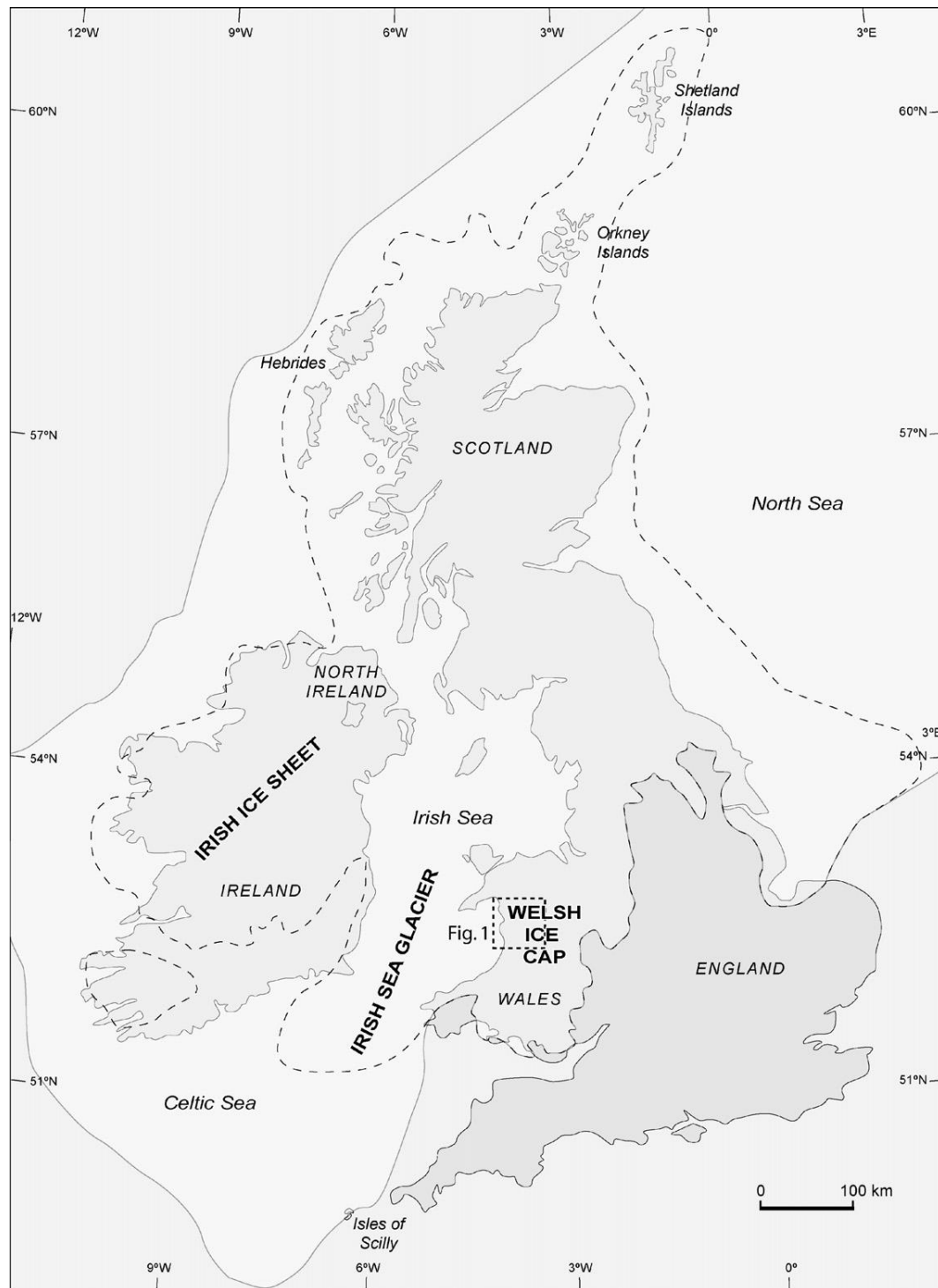


Fig. 3. Reconstruction of the British-Irish Ice Sheet during the Last Glacial Maximum (LGM) and approximate limit at the LGM when confluent with the Fennoscandian Ice Sheet according to the shelf-edge model (solid lines) (e.g. Scourse and Furze, 2001; Sejrup et al., 2005; Hiemstra et al., 2006; Bradwell et al., 2008; Scourse et al., 2009), and limited ice sheet model (dashed lines) (e.g. Bowen et al., 1986, 2002).

Former low-altitude cold-based areas saw a transition into warm-based, with only the interfluves remaining cold-based or with low ice discharge (Jansson and Glasser, 2005).

If the valleys in western Mid-Wales acted as major drainage conduits for the Welsh Ice Cap, then a likely outcome would be an increase of the interconnectivity of the valleys. The rationale for this assumption is that erosion by ice sheets will modify drainage patterns, breach watersheds and cut new troughs into the landscape (e.g. Linton, 1963; Haynes, 1977). A method to test the level of glacial modification on a drainage network is by performing a valley connectivity analysis (Haynes, 1977).

2.3. Geographic and geologic setting

Northwest Mid-Wales is characterised by a hilly to mountainous landscape, where the highest massifs of Aran (907 m O.D.), Cadair Idris (893m O.D.), Rhinogau (754m O.D.) and Pumlumon (752mO.D.), are all examples of glaciated upland landscapes, rich in various glacial and periglacial geomorphology (Watson, 1960, 1962, 1977; Campbell and Bowen, 1989; Hughes, 2002b). The landscape is strongly influenced by the bedrock lithology and its structural properties (Etienne et al., 2005). Lower Palaeozoic sedimentary and igneous rocks with a northeast to southwest trend reflect the structure developed during the Caledonian Orogeny, ca. 400million years ago. The orogeny was also responsible for the development of a strong cleavage in Ordovician mudstones. NW–SE and WSW–ENE aligned faults of late Caledonian age are common in the area, and many of them are morphologically prominent in the landscape, such as the Tal-y-llyn Fault south of Cadair Idris, and the Pennal Fault and the Llyfnant Fault north and south, respectively, of Machynlleth (Fig.1) (Cave and Hains, 1986, 1989; British Geological Survey, 1995; Pratt et al., 1995).

3. Methods

3.1. Image interpretation

LANDSAT 7 Enhanced Thematic Mapper Plus (ETM+) satellite images (15 m resolution in the panchromatic band) and digital elevation models (DEMs) sourced from NEXTMap Britain (horizontal resolution 5 m, vertical accuracy of <1 m), were used to visually detect and identify mega- and macro-structures on a regional scale, such as bedrock structure, drainage pattern and glacial lineations. To avoid the underestimation of landforms orientated in the light direction (azimuth biasing), the illumination in the DEMs was subsequently set from two orthogonal light directions (315° and 45°), as well as parallel to the principal linear orientation (the a-axis) of the landform, all with illumination height of 45°. Landforms were also made more visible by enhancing the slope curvature by setting the azimuth to 0° with illumination height of 90° (cf. Clark and Meehan, 2001; Smith and Clark, 2005; Smith et al.,

2006). Interpretation of detailed stereo pairs of colour aerial photographs (scale 1:10,000) was undertaken mainly with a Hilger & Watts stereoscope (2–6 X) and a WILD aviopret (3 X–15.5 X). The aerial photographs were used to detect and identify landform components, such as bedrock structure, valley spurs, cirques, moraines and glacial meltwater channels. The image interpretation was verified by subsequent field visits. The mapping procedure has been outlined in Sahlin and Glasser (2007, 2008). Valley cross-profiles and longitudinal profiles were made and analysed in ArcMap 9 and ENVI.

Prominent bedrock structure can be mistaken for glacial lineations. In order to separate the geological component from the glacial imprint, linear structures interpreted to be of glacial and structural geneses, as well as ambiguous features, were mapped in both aerial photographs and DEMs, and labelled as precisely as possible (e.g. faults, folds, joints, cleavage, rock drumlins, roches moutonnées and flutes). Verification of interpretation, as well as the gathering of glacial striae data, was undertaken in subsequent field visits. With additional geological data (e.g. tectonic lineaments, fold orientations and bedrock units) extracted from various analogue geological sources (e.g. Nutt, 1973; Cave and Hains, 1986, 1989; British Geological Survey, 1995; Pratt et al., 1995); as well as digital (EDINA Geology Digimap (www.edina.ac.uk)), the data was compiled and analysed in ArcGIS.9 (ArcMap). By subtracting the known geological components from the collected data, the difference was interpreted to represent the glacial imprint, especially where it coincided with field-validated glacial directions.

3.2. Connectivity analysis of valley patterns

In order to quantify the glacial modification of a preglacial fluvial valley pattern, a method for measuring the connectivity of the valley network (note: not the same as stream pattern) can be applied (Haynes, 1977).

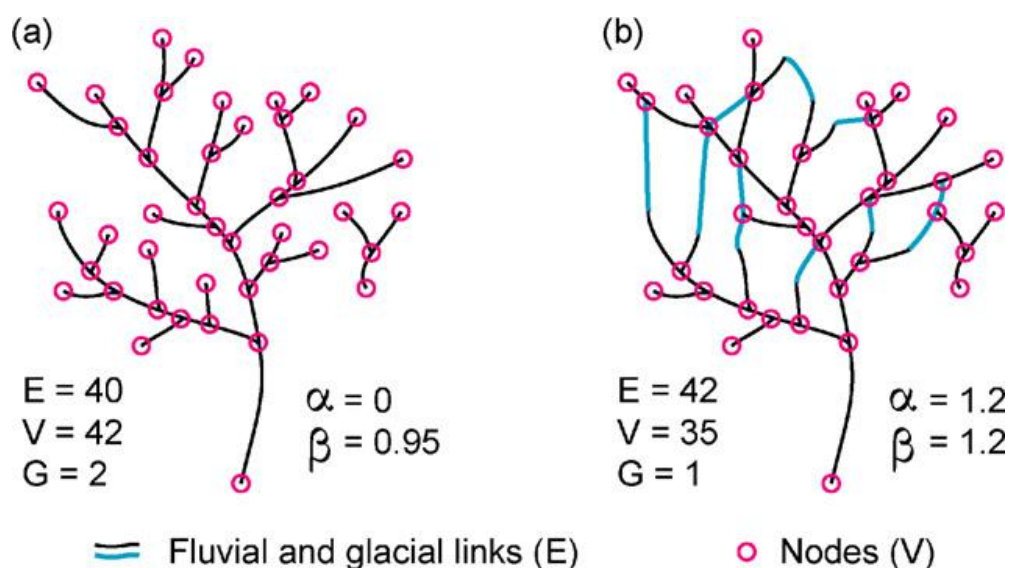


Fig. 4. Examples of network connectivity. (a) Purely dendritic fluvial network with two sub-basins. a value is 0 and b value < 1. (b) Glacial modification in form of watershed breaching increase number of circuits and the connectivity. a and b values become larger with increasing connectivity.

The connectivity is defined by α and β values, where the value of α is an expression of the ratio between the number of fundamental circuits and the maximum number which could exist theoretically in the same network, given by the formula:

$$\alpha = \frac{E-V+G}{2V-5} \times 100\% \quad (1)$$

and the b index is the simple measure of connectivity which can be derived from the formula:

$$\beta = \frac{E}{V} \quad (2)$$

where E = number of valley segments (fluvial or glacial links), V = number of valley junctions (nodes), beginning or end of any valley, and G = number of separate sub-basins.

A perfectly dendritic network has a values = 0 and a β value of <1. Glacial modification of the network, i.e. greater connectivity, increases the α and β values (Fig. 4). A low α value (between 0.75 and 1.5) indicates some watershed breaching, while values above signify multiple breaching (Haynes, 1977).

Alpha and beta values for the Dyfi and Dysynni/Tal-y-llyn catchments were determined by generating links and nodes on a valley network map created in ArcMap using the watershed analysis described by Chang (2008, pp. 308–314) (ArcCatalog/Spatial Analyst Tool/Hydrology). Individual valley segments and network nodes were then drawn in a new network set in ArcMap and counted. Valleys have been defined as well-incised features more than 60 m in depth, 250 m in length, and 150 m width. In the application of this technique, hanging valleys and glacial meltwater channels, which breach watersheds and conform to the parameters set for valley dimensions, have been included (cf. Riedel et al., 2007).

4. Landscape evaluation

Aerial photographs, satellite images and DEMs reveal large variations in the degree of glacial modification between the river valleys of Mawddach, Dysynni, Tal-y-llyn, and Dyfi. Glacial erosional landforms, such as glacial troughs, rock drumlins, roches moutonnées, and glacially scoured bedrock are more common in the west and northwest parts of the investigated area, while smooth full-bodied mountain forms and V-shaped valleys are more common further inland towards southeast, especially along the water divide between the

Dyfi basin and the Twymyn Valley, where also the plateau exhibits a smooth (velvet-like) signal in the aerial and satellite imagery, which is characteristic of palaeo-surfaces (cf. Jansson and Glasser, 2008).

The Mawddach basin is a wide glacial trough containing rock drumlins, roches moutonnées and glacial striae. Glacial erosion and deposition give the landscape a “hazy” look in the DEMs (Fig. 1). The Dysynni and Tal-y-llyn valleys are glacial troughs with faceted valley spurs and hanging valleys. In the DEMs the glacial excavation is evident in two distinctive ways: (1) the valley depth is represented by dark shades (i.e. low altitude), and (2) the parabolic slopes are depicted by the abrupt change from light to dark shades, which give the valleys a “swollen” look, compared with the V-shaped valleys where the shading is more gradual. Although glacial erosion has been a dominant factor in shaping the upper Dyfi catchment, as evidenced by the glacial troughs leading from the Aran Mountains, the middle and lower parts of the Dyfi basin exhibit a well-developed dendritic drainage pattern, with narrow river valleys, preserved valley spurs and V-shaped cross profiles (Fig. 5a and b). The Dyfi basin lacks the “hazy” look of Mawddach in the DEMs (Fig. 1). The Twymyn valley differs from the Dyfi basin in that it shows a strong glacial signature in the DEMs, especially in the upper part, while the majority of the Twymyn tributary valleys are glacially immature.

Several localities have been identified in the Dyfi catchment where glacial meltwater incision has cut into a pre-existing river valley system (Fig. 6), resulting in river capture across watersheds (Fig. 5c), or have been left as dry hanging channels (Fig. 5d). The best-known example of river piracy in the area is the Dylife Gorge (Fig. 5e) (cf. Jones and Pugh, 1935a,b; Lewin, 1997). Fresh glacial erosional landforms are rare and are mainly concentrated on the valley floors. There is no indication in the Dyfi catchment that large rock slope failures are responsible for the either lowering of watersheds, or having caused glacial or fluvial deflection.

Despite the strong expression of NNE–SSW-trending bedrock folds in the western parts of the area (cf. Cave and Hains, 1989), the dendritic drainage pattern of the Dyfi basin is relatively unaffected by the gross geological structure, with the exception of the Afon Dyfi itself, which in its lower part follows the Pennal Fault for more than 25 km towards the coast. The dendritic pattern transcend for example the west–east trending Llyfnant Fault in a north–south direction; the preglacial watershed have been breached by glacial meltwater draining towards west, exploiting the zone of weakness along the fault (Fig. 6).

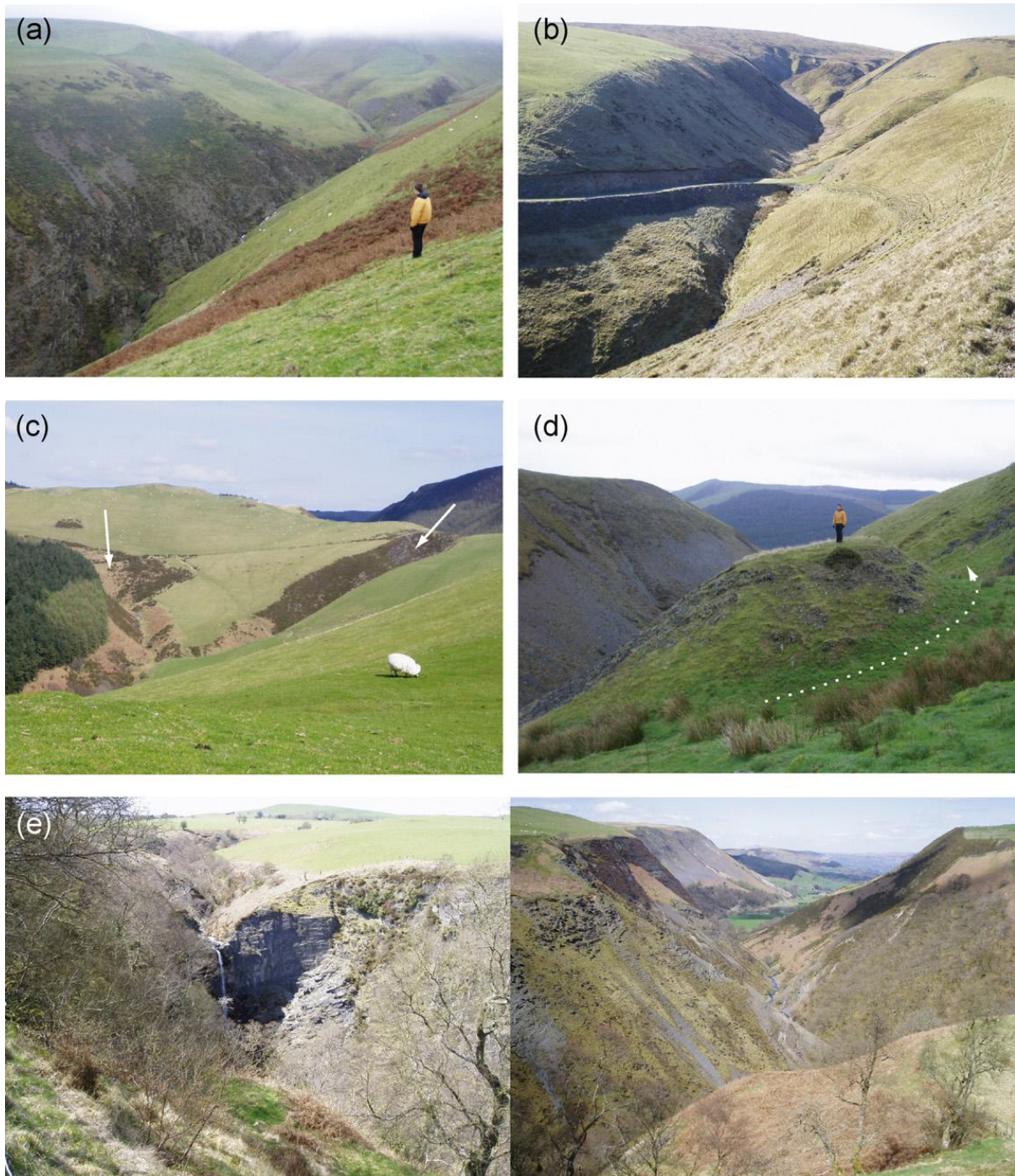


Fig. 5. (a) Narrow river valleys with V-shaped cross profiles, deeply incised into the smooth plateau surface, are characteristic for the south-eastern part of the Dyfi basin, such as the Esgair Wen valley near Meml [2845 2964]. (b) The Esgair Ddu valley [2845 2965], road for scale. (c) Watershed breaching by meltwater channels (arrowed) at Craig y Gath [28497 29688]. (d) Hanging meltwater channel (arrowed) at [283937 296197] in the upper Esgair Ddu. (e) Panorama of the Dylife Gorge [2873 2940] with Ffrwd Fawr waterfall (to the left). Note the size discrepancy between the valleys and the misfit stream of Ffrwd Fawr.

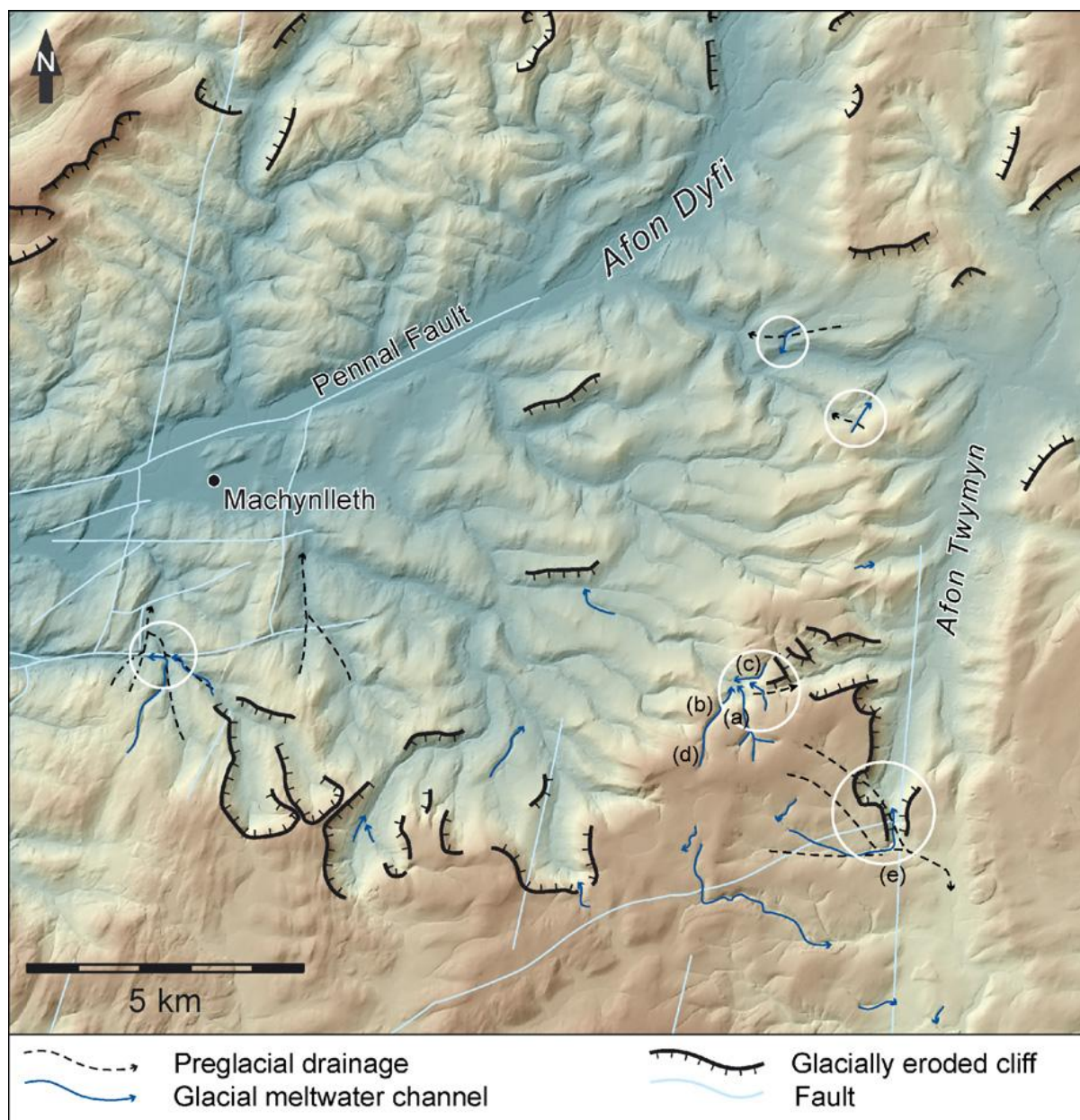


Fig. 6. Relief-shaded digital elevation model (DEM) of the central Dyfi basin and adjacent uplands. Circles mark sites where glacial meltwater has breached watersheds or changed the course of the preglacial drainage. Letters refer to the photographs in Fig. 5.

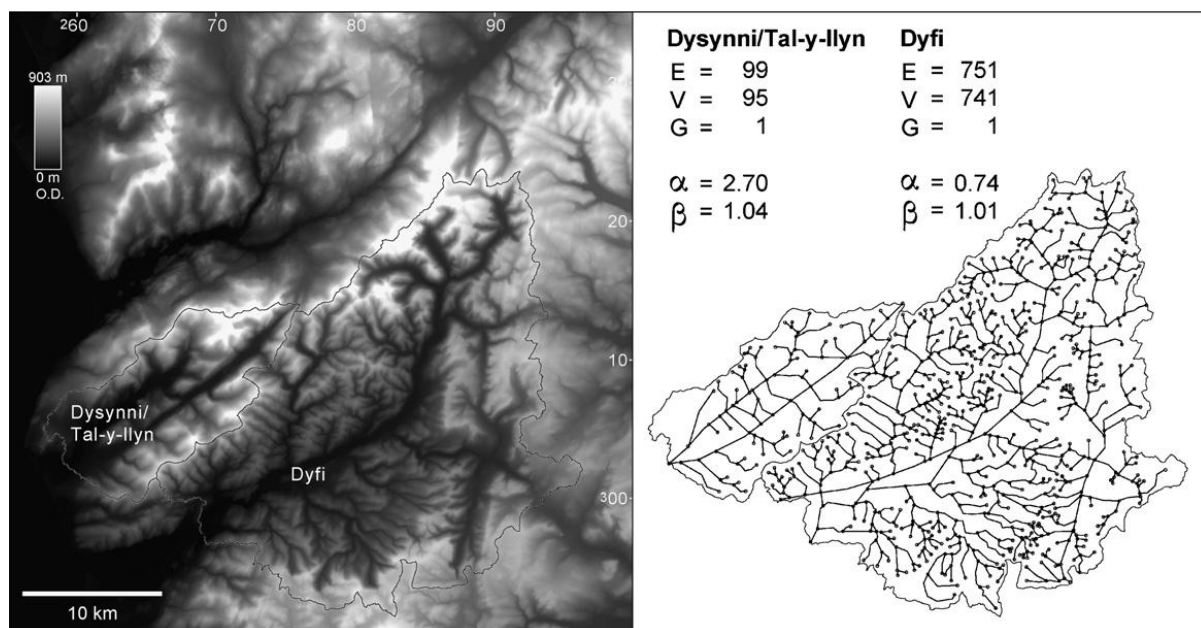


Fig. 7. Digital elevation model with the Dysynni/Tal-y-llyn and Dyfi catchments (left), and the resulting valley network map with connectivity analysis (right).

The watershed analysis performed for the Dysynni/Tal-y-llyn and Dyfi catchments yielded areas of 130.5 km² and 531.5 km², respectively. The connectivity analysis for the Dysynni/Tal-y-llyn and Dyfi catchments is illustrated in Fig. 7. The Dysynni/Tal-y-llyn catchment contains 99 valley segments (E), i.e. fluvial and glacial links, 95 valley junctions (V), and 1 sub-basin (G), yielding an α value of 2.70 and a β value of 2.70. The connectivity values for the Dyfi catchment are: valley segments (fluvial or glacial links) E = 751; number of valley junctions V = 741; number of sub-basins G = 1. The resulting α and β values are 0.74 and 1.01, respectively.

The connectivity analyses show there is a difference in the amounts of drainage modification between the catchments. The Dyfi basin exhibits an almost completely dendritic pattern with little glacial modification of the preglacial fluvial valley pattern in form of valley breaching.

5. Discussion

Battiau-Queney (1981) suggested that the effects of glaciation in Mid-Wales were highly selective according to the resistance of the rocks involved. If this were to hold true onewould expect the Dyfi basin, which are of sedimentary bedrock (mudstones and sandstones) to be more glacially modified than the areas of Mawddach, Dysynni and Tal-y-

llyn, which constitute mainly of resistant volcanic bedrock. However, although all of these valleys are glacially over-deepened along Silurian fault lines (Fig. 1), the bedrock beneath both the Dysynni and the Dyfi reach a depth of ca. 90 m below the present sea-level in their lower reaches (Bowen, 1974), only the Dyfi basin exhibits a dendritic pattern with V-shaped cross profiles and valley spurs typical of valleys formed by fluvial processes. Also, despite the strong lithological expression of NNE–SSW trending bedrock folds in the western parts (cf. Cave and Hains, 1989), the dendritic drainage pattern of the Dyfi basin is relatively unaffected by the gross geological structure, with the exception of the lower parts of the Afon Dyfi itself, which follows the Pennal Fault. This may suggest superimposed drainage initiated upon a cover of Mesozoic rocks (Brown, 1960) in the Neogene Period (cf. Battiau-Queney, 1984; Rowberry et al., 2007). The dendritic pattern may thus have survived and developed relatively unaffected by subsequent Pleistocene glaciations.

It could be argued that the channels which cross-cut the dendritic valley network of the Dyfi basin and breach interfluvies in the upper valleys are of Holocene age; their previous courses blocked by drift deposited during the last deglaciation. However, the sheer size of these channels (up to 180 m across and 60 m in depth) in relation to the lack of large catchments indicate they were either cut by large amounts of glacial meltwater, or have been in use for a long time, rather than formed in response to Holocene runoff and rejuvenation. This indicates that the dendritic drainage pattern is at least of pre-Late Devensian age.

So how is preservation of a pre-Late Devensian valley network possible in an area believed to have been glaciated repeatedly and which acted as a major focus for ice discharge? Some studies (e.g. McCarroll and Ballantyne, 2000; Shakesby et al., 2007) have suggested that the ice sheet over Wales was relatively thin, with topographically constrained geometry and behaviour. The glaciation over Wales would then have behaved more like mountain glaciation than ice-sheet glaciation, with a set of outlet glaciers from small ice-dispersal centres, resulting in relatively little modification of the preglacial valley geometry and connectivity. However, the increasing evidence offshore supporting the BIIS shelf-edge model (e.g. Scourse and Furze, 2001; Sejrup et al., 2005; Ó Cofaigh and Evans, 2007; Bradwell et al., 2008; Scourse et al., 2009), is not compatible with thin LGM ice-cover over Mid-Wales. Ballantyne (2009) has recently reassessed the limited ice-sheet model, and agrees that many previous interpreted periglacial trimlines could be englacial thermal boundaries, which would better fit the shelf-edge model.

One explanation for the limited glacial modification of the Dyfi basin could be attributed to its position close to, or under, a migrating ice-divide where the ice was cold-based or slow-moving (cf. Dyke, 1993). However, this scenario holds true for the glacially modified valleys to the north also. A difference could be that the higher surface elevation relative to the local relief of Snowdonia, compared with the High Plateau of Mid-Wales, controlled the degree of glacial modification, i.e. the valleys of the Snowdon Range amassed thicker ice where the

steep topographic gradients resulted in ice-surface gradients being steeper and the converging of ice-flow facilitated higher levels of basal sliding, compared with the Dyfi basin.

Another explanation is that the ice-flow was channelized along the Pennal Fault; exploiting preglacial topography, perhaps also lubricated by soft deformable sediments (cf. Boulton, 1972; MacAyeal, 1993; Clark, 1995; Jenson et al., 1996) deposited during interstadial/interglacial time, in combination with higher basal water pressure associated with a porous and permeable fault zone (cf. López and Smith, 1995). This would have resulted in higher ice-flow velocities along the fault zone compared with the surrounding higher areas of the basin (cf. Bennett, 2003), where slow-moving ice led to preservation of the preglacial geomorphology (Fig. 8). The ineffectiveness of glacial erosion in the Dyfi basin is also supported by the way in which features of preglacial origin, such as the Dyfi Peneplain, still can be identified (Jones, 1951; Brown, 1960). Although an order of magnitude smaller both in spatial scale and longevity, an analogue can be drawn with East Antarctica where fluvial landscapes have been preserved, and where deep grabens have channelled the ice streams (Jamieson et al., 2005). It is also possible that the ice drainage in the Dyfi valley only developed higher ice-flow velocities for a short period of time, perhaps during deglaciation, and therefore had limited time in which to accomplish deep and widespread glacial erosion. Another analogue can be drawn with northern Ellesmere Island in the Canadian Arctic, where the recession of a cold-based interior ice cap reveals both fluvial and older glacial drainage pattern underneath, while the peripheral warm-based zones are scoured and otherwise glacially modified (Hattersley-Smith, 1961).

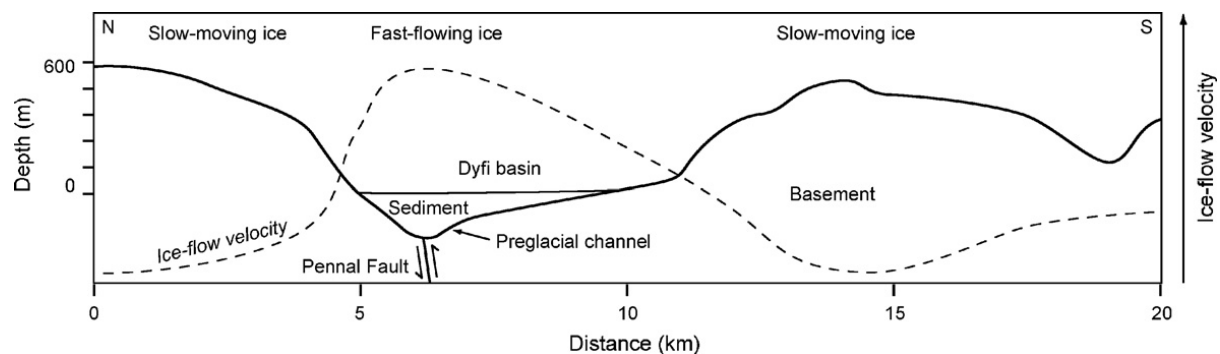


Fig. 8. Schematic cross-section, north to south, over the Dyfi basin, explaining the relationship between topography, sediment availability and ice-flow velocity.

6. Conclusions

There are large spatial variations in the amount of glacial modification between the coastal valleys of western Mid-Wales, which are not consistent with previous belief that they all acted as major drainage outlets for the Welsh Ice Cap. Although the valleys of the Mawddach, Dysynni, Tal-y-llyn and Dyfi are all glacially over-deepened along late Caledonian faults, only the Dyfi basin exhibits a dendritic valley pattern, with V-shaped cross profiles and valley spurs typical of valleys formed by fluvial processes. Connectivity analysis of the Dyfi basin shows that the basin exhibits an almost completely dendritic pattern (α and β values of 0.74 and 1.01, respectively), with little glacial modification of the preglacial fluvial valley pattern in the form of glacial valley breaching. Several examples of glacial meltwater incision into a well-developed preexisting river valley system have been identified in the Dyfi basin, which have caused river capture across watersheds.

The general river valley morphology of the Dyfi basin is inherited from at least prior to Late Devensian, and may even be preglacial in age. The degree of preservation indicates moderate modification by glacial processes, despite the area having been subjected to Late Devensian glacier activity. Major parts of the basin were probably covered by cold-based or slow-moving ice during much of the Late Devensian, with the major ice drainage occurring along the weaker zone of the Pennal Fault by the Afon Dyfi, causing minor adjustments to the surrounding interfluvies and uplands. Compared with the river valleys to the north, it is unlikely that powerful ice streams or outlet glaciers existed in the Dyfi basin for significant parts of the Late Devensian.

These findings are important for palaeoglaciological reconstructions of the Welsh Ice Cap. The identification of a preglacial river pattern in the Dyfi basin suggests that: (1) the drainage history is complex; (2) not only the interior uplands were subjected to cold-based ice; (3) Late Devensian glacial erosion was not as severe as previously believed; (4) larger areas of Wales and the UK, yet to be identified, might have been subjected to cold-based ice conditions.

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References

- Addison, K., 1990. Introduction to the quaternary in North Wales. In: Addison, K., Edge, M.J., Watkins, R. (Eds.), *The Quaternary of North Wales Field Guide. Quaternary Research Association*, pp. 1–19.
- Alley, R.B., Cuffey, K.M., Evenson, E.B., Strasser, J.C., Lawson, D.E., Larson, G.J., 1997. How glaciers entrain and transport basal sediment: physical constraints. *Quaternary Science Review*. 16, 1017–1038.
- Ballantyne, C.K., 2001. Cadair Idris: a Late Devensian palaeonunatak. In: Walker, M.J.C., McCarroll, D. (Eds.), *The Quaternary of West Wales Field Guide. Quaternary Research Association, London*, pp. 126–131.
- Ballantyne, C.K., 2009. Extent and deglaciation chronology of the last British–Irish Ice Sheet: implication of exposure dating using cosmogenic isotopes. *J. Quaternary Science Review*
- Ballantyne, C.K., Stone, J.O., Fifield, L.K., this issue. Glaciation and deglaciation of the SW Lake District, England: implications of cosmogenic ^{36}Cl exposure dating. *Proc. Geol. Assoc.*, 120.
- Battiau-Queney, Y., 1981. Les effects géomorphologiques des glaciations Quaternaires au Pays-de-Galles (Grand-Bretagne). *Revue de Géomorphologie* 30 (2), 63–73.
- Battiau-Queney, Y., 1984. The pre-glacial evolution of Wales. *Earth Surf. Process. Landforms* 9 (3), 229–252.
- Benn, D.I., Evans, D.J.A., 1998. *Glaciers and Glaciation*. Arnold, London.
- Bennett, M.R., 2003. Ice streams as the arteries of an ice sheet: their mechanics, stability and significance. *Earth Sci. Rev.* 61, 309–339.
- Bennett, M.R., Glasser, N.F., 1996. *Glacial Geology: Ice Sheets and Landforms*. John Wiley & Sons Ltd, Chichester.

Boulton, G.S., 1972. The role of thermal regime in glacial sedimentation. In: Price, R.J., Sugden, D.E. (Eds.), *Polar Geomorphology*. Institute of British Geographers, London, (IBG Special Publication), pp. 1–19.

Boulton, G.S., Clark, C.D., 1990a. A highly mobile Laurentide ice sheet revealed by satellite images of glacial lineations. *Nature* 346 (5), 813–817.

Boulton, G.S., Clark, C.D., 1990b. The Laurentide ice sheet through the last glacial cycle: the topology of drift lineations as a key to the dynamic behaviour of former ice sheets. *Trans. R. Soc. Edinburgh* 81, 327–347.

Bowen, D.Q., 1973. The Pleistocene history of Wales and the borderland. *Geol. J.* 8, 207–224.

Bowen, D.Q., 1974. The quaternary of Wales. In: Owen, T.R. (Ed.), *The Upper Palaeozoic and Post Palaeozoic Rocks of Wales*. University of Wales Press, Cardiff, (Published in memory of sir Arthur Trueman and also to celebrate the fiftieth anniversary (1920–1970) of the Department of Geology, University College of Swansea), pp. 373–417.

Bowen, D.Q., 1977. The coast of Wales. In: Kidson, C.K., Tooley, M.J. (Eds.), *The Quaternary History of the Irish Sea*. *Geol. J.* 7, 223–256 (special issue).

Bowen, D.Q., Rose, J., McCabe, A.M., Sutherland, D.G., 1986. Correlation of quaternary glaciations in England, Ireland, Scotland and Wales. *Quat. Sci. Rev.* 5, 299–340.

Bowen, D.Q., Phillips, F.M., McCabe, A.M., Knutz, P.C., Sykes, G.A., 2002. New data for the Last Glacial Maximum in Great Britain and Ireland. *Quat. Sci. Rev.* 21 (1), 89–101.

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D., Everest, J.D., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G., Mathers, H.M., 2008. The northern sector of the last British Ice Sheet: maximum extent and demise. *Earth Sci. Rev.* 88, 207–226.

British Geological Survey, 1995. Cadair Idris, Solid and Drift Geology. England and Wales Sheet 149, 1:50 000 Series. *British Geological Survey*, Keyworth, Nottingham.

Brown, E.H., 1960. *The Relief and Drainage of Wales: A Study in Geomorphological Development*. University of Wales Press, Cardiff.

Campbell, S., Bowen, D.Q., 1989. The Quaternary of Wales. *Geological Conservation Review Series*. Nature Conservancy Council, Peterborough.

Cave, R., Hains, B.A., 1986. Geology of the Country Between Aberystwyth and Machynlleth. Memoir of the British Geological Survey, England & Wales (Sheet 163).

Cave, R., Hains, B.A., 1989. Aberystwyth, Solid and Drift Geology. England and Wales Sheet Series 163, 1:50 000. British Geological Survey.

Chang, K.-T., 2008. *Introduction to Geographic Information Systems*, 4th ed. McGraw-Hill Education, Singapore.

Clark, C.D., 1993. Mega-scale glacial lineation and cross-cutting ice-flow landforms. *Earth Surf. Process. Landforms* 18 (1), 1–29.

Clark, C.D., 1999. Glaciodynamic context of subglacial bedform generation and preservation. *Ann. Glaciol.* 28, 23–32.

Clark, C.D., Meehan, R.T., 2001. Subglacial bedform geomorphology of the Irish Ice Sheet reveals major configuration changes during growth and decay. *J. Quat. Sci.* 16 (5), 483–496.

Clark, C.D., Stokes, C.R., 2003. Palaeo-ice stream landsystems. In: Evans, D.J.A. (Ed.), *Glacial Landsystems*. Arnold, London, pp. 204–227.

Clark, P.U., 1995. Fast glacier flow over soft beds. *Science* 267 (5194), 43–44.

Dyke, A.S., 1993. Landscapes of cold-centred Late Wisconsinan ice caps, Arctic Canada. *Prog. Phys. Geogr.* 17 (2), 223–247.

Dyke, A.S., Morris, T.F., Green, D.E.C., England, J., 1992. Quaternary Geology of Prince of Wales Island Arctic Canada. *Geol. Surv. Canada Memoir*, p. 433.

Echelmeyer, K., Zhongxiang, W., 1987. Direct observation of basal sliding and deformation of basal drift at sub-freezing temperatures. *J. Glaciol.* 33 (113), 83–98.

Etienne, J.L., Hambrey, M.J., Glasser, N.F., Jansson, K.N., 2005. West Wales. In: Lewis, C.A., Richards, A.E. (Eds.), *The Glaciations of Wales and Adjacent Areas*. Logaston Press, Bristol, (Chapter 7), pp. 85–100.

Evans, D.J.A., Livingstone, S.J., Vieli, A., O' Cofaigh, C., 2009. The palaeoglaciology of the central sector of the British and Irish Ice Sheet: reconciling glacial geomorphology and preliminary ice sheet modelling. *Quat. Sci. Rev.* 28, 739–757.

Eyles, N., McCabe, A.M., 1989. The late Devensian (<22 000 BP) Irish Sea Basin: the sedimentary record of a collapsed ice sheet margin. *Quat. Sci. Rev.* 8, 307–351.

Foster, H.D., 1968. *The glaciation of the Harlech Dome*. Ph.D. Thesis. University of London, Unpublished.

Foster, H.D., 1970. Establishing the age and geomorphological significance of sorted stone-strips in the Rhinog Mountains, North Wales. *Geogr. Ann.* 52A (2), 96–102.

Garrard, R.A., Dobson, M.R., 1974. The nature and maximum extent of glacial sediments off the west coast of Wales. *Mar. Geol.* 16, 31–44.

Glasser, N.F., 1995. Modelling the effect of topography on ice sheet erosion, Scotland. *Geogr. Ann.* 77A (1/2), 211–215.

Glasser, N.F., Bennett, M.R., 2004. Glacial erosional landforms: origins and significance for palaeoglaciology. *Prog. Phys. Geogr.* 28 (1), 43–75.

Glasser, N.F., Hambrey, M.J., Huddart, D., Gonzalez, S., Crawford, K.R., Maltman, A.J., 2001. Terrestrial glacial sedimentation on the eastern margin of the Irish Sea Basin: Thurstaston, Wirral. *Proc. Geol. Assoc.* 112, 131–146.

Hallet, B., 1979. A theoretical model of glacial abrasion. *J. Glaciol.* 23, 39–50.

Hambrey, M.J., Davies, J.R., Glasser, N.F., Waters, R.A., Dowdeswell, J.A., Wilby, P.R., Wilson, D., Etienne, J.L., 2001. Devensian glacial sedimentation and landscape evolution in the Cardigan area of southwest Wales. *J. Quat. Sci.* 16 (5), 455–482.

Hattersley-Smith, G., 1961. The ice cover of northern Ellesmere Island. *Ann. NY Acad. Sci.* 95, 282–289.

Hättestrand, C., 1998. The glacial geomorphology of central and northern Sweden. *Sveriges Geologiska Undersökning Ca* 85 1–47.

Hättestrand, C., Stroven, A.P., 2002. A relict landscape in the centre of Fennoscandian glaciation: Geomorphological evidence of minimal Quaternary glacial erosion. *Geomorphology* 44, 127–143.

Haynes, V.M., 1977. The modification of valley patterns by ice-sheet activity. *Geogr. Ann.* 59A (3/4), 195–207.

Hiemstra, J.F., Evans, D.J.A., Scourse, J.D., McCarroll, D., Furze, M.F.A., Rhodes, E., 2006. New evidence for a grounded Irish Sea glaciation of the Isles of Scilly UK. *Quat. Sci. Rev.* 25, 299–309.

Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R., Stoker, M., 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British–Irish ice sheet. *Quat. Sci. Rev.* 28 (7/8), 758–776.

Hughes, P.D., 2002a. Loch Lomond Stadial glaciers in the Aran and Arenig Mountains, North Wales, Great Britain. *Geol. J.* 37 (1), 9–15.

Hughes, P.D., 2002b. Nunataks and the surface altitude of the last ice sheet in southern Snowdonia, Wales. *Quat. Newsl.* 97, 19–26.

Huybrechts, P., T'siobbel, S., 1995. Thermomechanical modelling of northern hemisphere ice sheets with a two-level mass-balance parametrization. *Ann. Glaciol.* 21, 111–116.

Jamieson, S.S.R., Hulton, N.R.J., Sugden, D.E., Payne, A.J., Taylor, J., 2005. Cenozoic landscape evolution of the Lambert basin, East Antarctica: the relative roles of rivers and ice sheets. *Global Planet. Change* 45, 35–49.

Jansson, K.N., 2002. Early Holocene glacial lakes and ice marginal retreat pattern in Labrador/Ungava, Canada. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 193, 473–501.

Jansson, K.N., Glasser, N.F., 2005. Palaeoglaciology of the Welsh sector of the British–Irish Ice Sheet. *J. Geol. Soc. London* 162, 25–37.

Jansson, K.N., Glasser, N.F., 2008. Modification of peripheral mountain ranges by former ice sheets: the Brecon Beacons, Southern UK. *Geomorphology* 97 (1/2), 178–189.

Jarman, D., 2002. Rock slope failure and landscape evolution in the Caledonian Mountains, as exemplified in the Abisko area, northern Sweden. *Geogr. Ann.* 84A, 224–231.

Jarman, D., 2006. Large rock slope failures in the Scottish Highlands: characterisation, causes and spatial distribution. *Eng. Geol.* 83, 161–182.

Jarman, D., 2009. Paraglacial rock slope failure as an agent of glacial trough widening. In: Knight, J., Harrison, S. (Eds.), *Periglacial Processes and Environments*. *Geol. Soc. Spec. Publ.* 320, pp. 103–131.

Jenson, J.W., MaxAyeal, D.R., Clark, P.U., Ho, C.L., Vela, J.C., 1996. Numerical modelling of subglacial sediment deformation: implications for the behavior of the Lake Michigan Lobe, Laurentide Ice Sheet. *J. Geophys. Res.* 101 (B4), 8717–8728.

Jones, O.T., Pugh, W.J., 1935a. The geology of the districts around Machynlleth and Aberystwyth. Summer field meeting to the Aberystwyth district. *Proc. Geol. Assoc.* 46, 247–300.

Jones, O.T., Pugh, W.J., 1935b. Summer field meeting to the Aberystwyth district. *Proc. Geol. Assoc.* 46, 413–428.

Jones, O.T., 1951. The drainage systems of Wales and the adjacent regions. *Quart. J. Geol. Soc. London* 107, 201–225.

Kaplan, M.R., Hein, A.S., Hubbard, A., Lax, S.M., 2009. Can glacial erosion limit the extent of glaciation? *Geomorphology* 103 (2), 172–179.

Kirkbride, M., Matthews, D., 1997. The role of fluvial and glacial erosion in landscape evolution: the Ben Ohau Range, New Zealand. *Earth Surf. Process. Landforms* 22, 317–327.

Kleman, J., 1992. The palimpsest glacial landscape in northwestern Sweden—late Weichselian deglaciation landforms and traces of older west-centered ice sheets. *Geogr. Ann.* 74A (4), 305–325.

Kleman, J., 1994. Preservation of landforms under ice sheets and ice caps. *Geomorphology* 9, 19–32.

Kleman, J., Borgström, I., 1990. The Boulder fields of Mt. Fulufjället, West-Central Sweden. *Geogr. Ann.* 72A (1), 63–78.

Kleman, J., Borgström, I., 1994. Glacial landforms indicative of a partly frozen bed. *J. Glaciol.* 40 (135), 255–264.

Kleman, J., Borgström, I., 1996. Reconstruction of palaeo-ice sheets: the use of geomorphological data. *Earth Surf. Process. Landforms* 21, 893–909.

Kleman, J., Borgström, I., Robertson, A.-M., Liljesköld, M., 1992. Morphology and stratigraphy from several deglaciations in the Transtrand Mountains, western Sweden. *J. Quat. Sci.* 7 (1), 1–17.

Kleman, J., Glasser, N.F., 2007. The subglacial thermal organisation (STO) of ice sheets. *Quat. Sci. Rev.* 26 (5/6), 585–597.

Kleman, J., Hättestrand, C., 1999. Frozen-bed Fennoscandian and Laurentide ice sheets during the Last Glacial Maximum. *Nature* 402, 63–66.

Kleman, J., Hättestrand, C., Borgström, I., Stroeve, A., 1997. Fennoscandian palaeoglaciology reconstructed using a glacial geological inversion model. *J. Glaciol.* 43, 283–299.

Kleman, J., Stroeve, A.P., 1997. Preglacial surface remnants and Quaternary glacial regimes in northwestern Sweden. *Geomorphology* 19 (1–2), 35–54.

Korup, O., Strom, A.J., Weidinger, J.T., 2006. Fluvial response to large rock-slope failures: examples from the Himalayas, the Tien Shan, and the Southern Alps in New Zealand. *Geomorphology* 78 (1/2), 3–21.

Lagerbäck, R., 1988a. The Veiki moraines in northern Sweden—widespread evidence of an Early Weichselian deglaciation. *Boreas* 17 (4), 469–486.

Lagerbäck, R., 1988b. Periglacial phenomena in the wooded areas of northern Sweden—relicts from the Tändöinterstadial. *Boreas* 17 (4), 487–500.

Lagerbäck, R., Robertson, A.-M., 1988. Kettle holes—stratigraphical archives for Weichselian geology and paleoenvironment in northernmost Sweden. *Boreas* 17 (4), 439–468.

Lambeck, K., 1993. Glacial rebound of the British Isles—I. Preliminary model results. *Geophys. J. Int.* 115 (33), 941–959.

Lambeck, K., 1996. Glaciation and sea-level change for Ireland and the Irish Sea since Late Devensian/Midlandian time. *J. Geol. Soc. London* 153, 853–872.

Lewin, J., 1997. Fluvial landforms and processes in Wales. In: Gregory, K.J. (Ed.), *Fluvial Geomorphology of Great Britain*. Geological Conservation Review Series, Joint Nature Conservation Committee. Chapman & Hall, London, pp. 117–119.

Lewis, C.A., Richards, A.E. (Eds.), 2005. *The Glaciations of Wales and Adjacent Areas*. Logaston Press, Bristol.

Lidmar-Bergström, K., 1995. Relief and saprolites through time on the Baltic Shield. *Geomorphology* 12, 45–51.

Lidmar-Bergström, K., 1997. A long-term perspective on glacial erosion. *Earth Surf. Process. Landforms* 22, 297–306.

Linton, D.L., 1963. The forms of glacial erosion. *Trans. Inst. Br. Geogr.* 33, 1–28.

López, D.L., Smith, L., 1995. Fluid flow in fault zones: analysis of the interplay of convective circulation and topographically driven groundwater flow. *Water Resour. Res.* 31 (6), 1489–1504.

MacAyeal, D.R., 1993. Binge/purge oscillations of the Laurentide ice sheet as a cause of the North Atlantic's Heinrich events. *Paleoceanography* 8 (6), 775–784.

McCarroll, D., Ballantyne, C.K., 2000. The last ice age in Snowdonia. *J. Quat. Sci.* 15 (8), 765–778.

Nutt, M.J.C., 1973. Central Wales Mining Field, Scale 1:100 000. Institute of Geological Sciences, Geological Survey of Britain, England and Wales.

Ó Cofaigh, C., Evans, J.A., 2007. Radiocarbon constraints on the age of the maximum advance of the British–Irish Ice Sheet in the Celtic Sea. *Quat. Sci. Rev.* 26, 1197–1203.

Patton, H., Hambrey, M.J., this issue. Ice-marginal sedimentation associated with the Late Devensian Welsh Ice Cap and the Irish Sea Ice Stream: Tonfanau, West Wales. *Proc. Geol. Assoc.* doi:10.1013/j.pgeola.2009.10.004.

Pratt, W.T., Woodhall, D.G., Howells, M.F., 1995. Geology of the Country Around Cadair Idris. Memoir of the British Geological Survey, Sheet 149, England and Wales.

Rea, B.R., Whalley, W.B., Rainey, M.M., Gordon, J.E., 1996. Blockfields, old or new? Evidence and implications from some plateaus in northern Norway. *Geomorphology* 15 (2), 109–121.

Riedel, J.L., Haugerud, R.A., Clague, J.J., 2007. Geomorphology of a Cordilleran Ice Sheet drainage network through breached divides in the North Cascades Mountains of Washington and British Columbia. *Geomorphology* 91, 1–18.

Rohde, L., 1988. Glaciofluvial channels formed prior to the last deglaciation: examples from Swedish Lapland. *Boreas* 17 (4), 511–516.

Rowberry, M.D., Brewer, P., Macklin, M., 2007. The number, form and origin of sub-horizontal surfaces in north Ceredigion, Wales, UK. *Norwegian J. Geol.* 87, 207–222.

Sahlin, E.A.U., 2008. The dynamics and configuration of Welsh Quaternary glaciations. *Quat. Newsl.* 114, 54–58.

Sahlin, E.A.U., Glasser, N.F., 2007. Developing a geomorphology map of Wales. CCW Contract Science Report No.: 807. Countryside Council for Wales.

Sahlin, E.A.U., Glasser, N.F., 2008. A geomorphological map of Cadair Idris. *J. Maps* 299–314.

Scourse, J.D., Furze, M.F.A., 2001. A critical review of the glaciomarine model for Irish Sea deglaciation: evidence from southern Britain, the Celtic shelf and adjacent continental slope. *J. Quat. Sci.* 16 (5), 419–434.

Scourse, J., Uehara, K., Wainwright, A., 2009. Celtic Sea linear tidal sand ridges, the Irish Sea Ice Stream and the Fleuve Manche: palaeotidal modelling of a transitional passive margin depositional system. *Mar. Geol.* 259, 102–111.

Sejrup, H.P., Hjelstuen, B.O., Dahlgren, K.I.T., Haflidason, H., Kuijpers, A., Nygård, A., Praeg, D., Stoker, M., Vorren, T.O., 2005. Pleistocene glacial history of the NW European continental margin. *Mar. Petrol. Geol.* 22, 1111–1129.

Shakesby, R.A., Coleman, C.G., Carr, S.J., 2007. Quaternary landscape evolution. In: Carr, S.J., Coleman, C.G., Humpage, A.J., Shakesby, R.A. (Eds.), Quaternary of the Brecon Beacons Field Guide. *Quaternary Research Association*, pp. 14–22.

Shakesby, R.A., Matthews, J.A., 2009. Comments on Jansson, K.N. and Glasser, N.F., 2008. Modification of peripheral mountain ranges by former ice sheets: the Brecon Beacons, southern UK. *Geomorphology*, 97, 178–189. *Geomorphology* 110, 217–225.

Smith, B., George, T.N., 1961. *British Regional Geology: North Wales*, 3rd ed. Natural Environment Research Council, Institute of Geological Sciences, Geological Survey and Museum, London.

Smith, M.J., Clark, C.D., 2005. Methods for the visualization of digital elevation models for landform mapping. *Earth Surf. Process. Landforms* 30 (7), 885–900.

Smith, M.J., Rose, J., Booth, S., 2006. Geomorphological mapping of glacial landforms from remotely sensed data: an evaluation of the principal data sources and an assessment of their quality. *Geomorphology* 76, 148–165.

Sugden, D.E., 1974. Landscapes of glacial erosion in Greenland and their relationship to ice, topographic and bedrock conditions. In: Brown, E.H., Waters, R.S. (Eds.), *Progress in Geomorphology: Papers in Honour of D.L. Linton*. Inst. Brit. *Geogr. Spec. Publ.* 7, pp. 177–195.

Sugden, D.E., 1977. Reconstruction of the morphology, dynamics and thermal characteristics of the Laurentide Ice Sheet at its maximum. *Arctic Alpine Res.* 9, 21–47.

Sugden, D.E., John, B., 1976. *Glaciers and Landscape*. Edward Arnold, London.

Sugden, D.E., Watts, S.H., 1977. Tors, felsenmeer, and glaciation in northern Cumberland Peninsula, Baffin Island. *Can. J. Earth Sci.* 14, 2817–2823.

Thomas, G.S.P., 1985. The Late Devensian glaciation along the border of northeast Wales. *Geol. J.* 20, 319–340.

Thomas, G.S.P., 2005. North-east Wales. In: Lewis, C.A., Richards, A.E. (Eds.), *The Glaciations of Wales and Adjacent Areas*. Logaston Press, Bristol, (Chapter 4), pp. 41–58.

Watson, E., 1960. Glacial landforms in the Cader Idris area. *Geography* 45, 27–38.

Watson, E., 1962. The glacial morphology of the Tal-y-llyn Valley, Merionethshire. *Trans. Inst. Br. Geogr.* 30, 15–31.

Watson, E., 1977. Mid and North Wales. In: *Guidebook for Excursion C9*, INQUA X Congress, Geo Abstracts Ltd., Norwich.